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TITANIUM FASTENERS

JOSEPH L. PHILLIPS
MANUFACTURING RESEARCH & DEVELOPMENT
COMMERCIAL AIRPLANE GROUP
THE BOEING COMPANY

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Titanium fasteners were first introduced to a Boeing product in the B-52 approximately twelve years ago. Today, titanium fasteners are used in large quantities throughout the aircraft industry. Most of this usage is in aluminum structure; where titanium structure exists, titanium fasteners are logically used as well.

What are the factors involved in selecting titanium as a fastener material and what are some of the special considerations involved? Answers to these questions plus some discussion of alloys, special fasteners and installation methods constitutes the content of this paper.

BASIC SELECTION CRITERIA

Mechanical fastening of aluminum structure most commonly employs aluminum rivets. To accommodate increases in shear loads, the rivet diameter is increased. This reaches a practical limit at 3/8 inch diameter with most existing driving methods; in addition, there is a trade off on maximum diameter versus weight of structure to accommodate it. At this point, a design selection of a smaller diameter, higher shear strength fastener is made. In the past, this was usually a cadmium plated steel bolt type of fastener of 180 ksi UTS.

This 180 ksi UTS steel has a shear allowable of 95 ksi; since the most commonly used titanium alloy (Ti-6Al-4V) also has a shear allowable of 95 ksi, a direct substitution is possible on the basis of strength alone. However, the cost of such a titanium fastener will run 2 to 2-1/2 times that of the steel fastener. If cost of the product alone is paramount, the choice is obvious. If weight is critical, then a trade-off may be justified. In a large airplane such as the Boeing 747, the use of titanium instead of steel for most of the non-aluminum fasteners saves approximately 4000 pounds of weight. The price for this saving is approximately \$30 per pound. The criteria for acceptability of this added cost will vary in accordance with the importance attached to weight reduction in the product. Generally, a figure of \$100 a pound is often used when weight reduction is required to meet guarantees in commercial aircraft; even higher figures may be justified to provide mission capability in military aircraft.

Since the direct substitution designated is for a 180 ksi UTS, 95 ksi shear alloy steel bolt, the question often arises about the justification for the use of titanium if higher strength steels are used - such as 260 ksi UTS, 156 ksi shear.

The titanium will still provide some weight saving in this case since the density of steel is approximately twice that of titanium, but the cost per pound saved increases to \$190 per pound. However, the 260 ksi steels have led to some difficulties with fastener reliability; in addition, to affect the weight reduction indicated produces a fastener referred to by some stress engineers as a spaghetti fastener - one with a poor L/D ratio. Such fasteners may not prove to be critical in static bearing allowables, but they will often degrade the design fatigue rating of a structure.

Where space becomes critical or high clamp forces are required, then a steel fastener of 220 ksi UTS, 125 shear may prove to be a better selection than titanium. This relates to both the fastener diameter and the head and nut portions of the fastener. The steel will allow a higher strength in a smaller diameter; providing high clamp up with the titanium will eat up the weight savings in thicker heads longer threads and thicker nuts to compensate for the lower strength.

Besides weight savings, titanium fasteners may also be selected for their corrosion resistance or their strength at elevated temperatures. The corrosion resistance referred to is for the titanium fastener itself - when fabricated from the proper alloy. Galvanic considerations when used with dissimilar metals is another matter that will be covered later. For instance, titanium fasteners in titanium fittings attached to a fiberglass, ocean racing sailboat would provide both weight reduction and excellent corrosion resistance.

Elevated temperature usage would be primarily related to usage in titanium structure - where the titanium structure was required to meet temperatures too high for aluminum. Such usage should generally be limited to 600°F; above this temperature, susceptibility to salt corrosion and degradation of mechanical properties makes other materials such as A-286 and Inconel 718 more attractive.

ALLOY SELECTION

The predominate alloy in use for titanium fasteners is Ti-6Al-4V, the "workhorse" titanium alloy. This is based on several reasons:

1. Until recently, most high strength titanium fasteners were bolt type fasteners that did not require deformation in installation;

2. The 6Al-4V alloy is one that users have the most experience with in general (introduced in 1954) and the most knowledge of with regard to thermal performance;
3. Its long term existence and extensive general usage has led to a consistency of mill product not always obtainable with other alloys;
4. There are very few titanium alloys with strengths better than 6Al-4V.

Besides strength, density, corrosion properties and thermal properties, the primary considerations in alloy selection are intended usage as either a bolt or rivet type of fastener. Generally, the higher strength alloys have been used as bolts; the commercially pure alloys and, recently, the beta alloys as rivets. Some specific alloys that have proven to be most successful are listed below:

1. Ti-6Al-4V - as stated before, this is the workhorse alloy. Its density is 0.160 lbs/in³ and its shear strength is 95 ksi. It is readily available, its properties can be relied on, and it has good strength retention at temperature. Ti-6Al-4V can be used as a conventional rivet in titanium structure when heat treated to 90 ksi if the edges of the hole in the structure are chamfered and the rivet is upset by machine squeezing. It cannot be reliably upset by impact driving without cracking unless its shear strength is reduced to 82 ksi.
2. Ti-6Al-6V-2Sn - this alloy appears attractive as the best current substitute for Ti-6Al-4V. It is slightly heavier (density = 0.164 lbs/in³), but it has a better shear strength (105 ksi). It is also a better choice for use at elevated temperatures since it retains its strength better than Ti-6Al-4V.
3. Ti-11-1/2Mo-6Zr-4-1/2Sn - this is the Beta III alloy. It was the first titanium alloy that proved reasonable to drive by impact means without cracking difficulties or a need to chamfer corners and still have a reasonably high strength (90 ksi shear). It is, however, somewhat heavier (.183 lb/in³) and could represent a significant weight difference in a large, all titanium aircraft such as the SST. All of the beta alloys also display some thermal stability problems and should not be used above 500°F.

4. Ti-8Mo-8V-2Fe-3Al - this is another beta alloy with similar formability characteristics to Beta III. It is also somewhat lighter (.172 lbs/in³) and may prove to be lower in procurement price since it does not have the melt control problem experienced with the Beta III alloy.
5. Commercially Used Alloys - the CP40 alloy is the most commonly used alloy where a lower strength titanium alloy rivet (35 ksi shear) will suffice. The CP55 alloy (50 ksi shear) can also be driven by impact means, but with more difficulty. The CP70 alloy is difficult to drive. All of the CP alloys also lose their strength rapidly at elevated temperature.
6. M172 - this is a new alloy of 55% Columbium and 45% titanium with a shear strength of 50 ksi. It has proven to be an excellent substitute for the CP40 alloy since it can be driven as easily as an aluminum rivet and produces less distortion in thin titanium sheet structure. Another potential use in a bimetal fastener will be discussed later.

Some other alloys that have been considered, but have not been acceptable or worthwhile are:

1. Ti-8Al-1Mo-1V - this alloy is stronger than Ti-6Al-4V and was strongly considered for both structure and fasteners in the SST until it was found to have serious stress corrosion problems under certain conditions.
2. Ti-1Al-8V-5Fe - this is also a higher strength alloy than the Ti-6Al-4V, but has proven to be very brittle in installation and subject to stress embrittlement in service. The first has required use of 60° heads to prevent failures when installing bolts in interference fits; the latter has resulted in a high percentage of head failures in service.
3. Ti-7Al-12Zr - looks as good as Ti-6Al-4V, but offers no significant advantages to justify its application.
4. Ti-13V-11Cr-3Al - a difficult to machine, high strength titanium alloy that can be squeeze driven but exhibits brittleness after an elevated temperature soak.

5. Ti-3Al-2-1/2V - an 80 ksi shear alloy that appears to have good characteristics for a rivet on the basis of its mechanical properties and has been used in a crimp type of nut (Huckrimp); however, it has not proven usable in test driving as a rivet.

FABRICATION

The fabrication of titanium fasteners could achieve some importance in their comparative costs, but, generally, the techniques used are relatively universal for all alloys. Ti-6Al-4V titanium fasteners are "warm" headed whereby the end of the wire slug is heated to approximately 900°F with an induction coil immediately prior to heading. Some manufactures are cold heading the Beta III alloy. Including heading, a typical sequence of operations to produce a threaded, titanium fastener such as the Boeing PT bolt follows:

1. Metallurgical check of raw material for heat treat response
2. Warm head
3. Inspect for dimensions and laminations
4. Heat treat
5. Inspect mechanical properties
6. Shave flash from head
7. Profile grind shank and head
8. Roll head to shank fillet
9. Roll threads
10. Inspect for laminations
11. Roll entry radius
12. Inspect for dimensions
13. Phosphate flouride coat
14. Lubricate and package

Since the shanks and head on precision fasteners (0.0005 total tolerance) are ground and titanium is considered to be notch sensitive, the fillet rolling operation has been considered absolutely essential for fatigue performance. It should be noted that the grinding operation contributes significantly to the cost of a titanium fastener; if the shank tolerance can be increased to approximately 0.015 inch, the grinding operation can probably be eliminated and the fastener cost reduced.

Heat treatment is of some importance with regard to prevention of hydrogen embrittlement. It also presents some difficulties with regard to preventing distortion in fasteners such as lockbolts that have a large L/D ratio with the break off pin-tail added to the regular fastener length. Special precautions have proven necessary with the bimetal fastener to prevent hydrides at the bimetal interface. In this case, the parts per million of hydrogen in the two components are held well below normal requirements and are balanced to provide equilibrium at the interface (to prevent migration). These fasteners are heat treated in a "boat" in a vacuum furnace. When they are to be quenched, the boat is withdrawn into an inert atmosphere chamber. The boat is then inverted to dump the fasteners within a few seconds through the inert atmosphere directly into a rotating collecting basket in the water quench tank.

SPECIAL CONSIDERATIONS

Even though most titanium alloys are very resistant to corrosion, they can form galvanic couples when used with other metals. Such galvanic couples can lead to undesirable galvanic corrosion. The galvanic couple is of a relatively high order of magnitude with aluminum although the surface oxides tend to diminish its effects; nevertheless, it is sufficient to ultimately lead to problems. Thus, titanium fasteners used in aluminum structure must take this factor into account. Some of the methods utilized or considered to handle this problem are discussed below:

Wet Sealant or Primer

This method involves painting the hole or fastener with chromated polysulfide sealant or a chromated epoxy primer and installing the fastener while the sealant or primer is still wet. Some companies that use aluminum nuts on bare titanium fasteners coat the entire fastener; others that use cadmium plated steel nuts coat only the most critical exposed end grains in the countersink. At best, this is a costly, messy approach albeit one that appears to work.

Dry Sealant or Primer

In this approach, a controlled thickness of sealant or primer is precoated on the underside of the fastener head and cured. This operation is performed by the fastener manufacturer. The concept was pioneered by Boeing and is currently in use. Only the countersink zone is treated since a coating on the entire fastener would

create installation difficulty, would create electrical grounding problems and is not necessary since the material acts like a gasket to prevent the intrusion of electrolytic fluids to the rest of the fastener/structure interface. In addition, the dry coating assures the existence of more corrosion inhibiting chromates in the coated interface area since less of the material extrudes from the interface than occurs with wet materials. This method avoids the installation/housekeeping problems and costs associated with the wet methods.

Cadmium Plating

Cadmium plating has been used widely for years on steel fasteners as a sacrificial coating to prevent galvanic corrosion damage to aluminum structure. It has also been used on titanium fasteners for the same purpose. Much attention has been focused on the use of cadmium for this purpose as a result of some studies that indicate that cadmium causes cracking of titanium. Actually, this is a surface microcracking phenomena that requires high tensile stress, high bearing pressure (to cause intimate contact) and elevated temperature with increased incidence as the temperature increases. At ambient temperatures microcracking can only be produced in the laboratory at pressures exceeding the yield point of the titanium. It should be noted that the alloy steels used for cadmium plated fasteners for many years are even more susceptible to this microcracking than titanium under equivalent conditions. Many years of service with cadmium plated steel fasteners and several years of service with cadmium plated titanium fasteners used at ambient temperatures has disclosed no problems. Nevertheless, we believe that a cautious approach should be exercised and cadmium should not be used on any titanium fasteners that are exposed to temperatures above 150°F.

Aluminum Plating or Coating

From a viewpoint of galvanic corrosion in aluminum structure, aluminum plating has appeared to be an attractive alternative for a number of years. In fact, a field test conducted in an Air Force-Lockheed study in 1965 to 1967 showed aluminum plating to be superior in corrosion protection. Aluminum plating has not come into common usage for this purpose since then because aluminum cannot be plated with more conventional electroplating methods. The more exotic methods required presented high costs and volume limitations. In the interim, other methods that use organic or inorganic binders to paint on aluminum followed by a fusion or bake-out operation have been developed.

The use of aluminum is attractive to the aircraft industry for other reasons besides structural corrosion protection. These are:

1. Color Matching - bare titanium is dark in color and presents a cosmetic appearance problem when used in unpainted, exterior aircraft skins of aluminum.
2. Paint Adhesion - bare titanium does not have good paint adhesion. Abrading will provide adhesion, but painting must follow abrading immediately. This is impractical. The best method of providing paint adhesion on titanium is a phosphate flouride conversion coating. Unfortunately, this is black in color and color matching is difficult in fuselage areas where both painted and unpainted zones exist and painted to unpainted belt lines vary from customer to customer.
3. Compatibility with Aluminum Nuts - coating all over with aluminum avoids any necessity to provide auxiliary protection for aluminum nuts to guard against galvanic corrosion. Actually, this may not be a significant problem since the anodize coating on the nut alone may prevent any difficulty. Testing relative to this is in progress.

Even though successful, lower cost plating operations are now becoming available, there is a further problem that is currently unsolved. A high shear capacity fastener of titanium will normally be used in a slight interference fit to assure equal load transfer on all fasteners or even in an interference fit up to 0.006 inch (for a 1/4 inch diameter fastener) for fatigue applications. The aluminum coatings, as deposited, are too soft and tend to pile up on fastener installation causing either difficulty with fastener seating or random, premature fatigue failures. Use of further treatments such as hard anodizing add too much cost and become unattractive in that respect.

Phosphate Flouride

There is some evidence that a phosphate flouride conversion coating alone provides galvanic corrosion protection equivalent to the other methods mentioned. Where usage is definitely in a painted area and especially if there is an interference fit, the phosphate flouride coating is especially attractive since it provides good paint adhesion, provides a good base for holding insertion lubricants and will not permit pile-up problems on insertion.

Titanium Anodize

The proprietary titanium anodize process, Tiodize, is also of interest since it is non-conductive and integral with the surface. Color matching is a problem with the Tiodize conversion alone. Installation and corrosion tests of Tiodized fasteners with a thin flash coating of vapor deposited aluminum for cosmetic purposes are now in progress.

Lubrication

Titanium fasteners which are used in aluminum or titanium structures usually must be lubricated for nut torquing or installation in interference fits. Rivet type fasteners initially installed in clearance holes do not require lubricant. The most satisfactory lubricant for the fastener itself, when used in aluminum structure, is cetyl alcohol. This is a long chain alcohol that can be put on by dipping fasteners in a solution of cetyl alcohol and solvent or by barrel tumbling the fasteners in powdered cetyl alcohol. Use of this lubricant allows practical installation of up to 3/8 inch diameter fasteners using conventional rivet guns and with interference fits up to 0.006 inch. Any cetyl alcohol residue is easily removable with a water rinse or solvent wipe to prevent subsequent problems with paint or sealant adhesion.

When titanium fasteners are to be installed in titanium structure with interference fits or titanium nuts are to be used on titanium fasteners, the fastener or nut should be coated with a dry lubricant. Any of a number of these are used successfully by various manufacturers; tests at Boeing indicated that Lubeco 2123 produced the lowest installation and removal forces (after exposure to elevated temperature) and Esnalube 380 produced the lowest friction in nut torquing of those tested.

FASTENER SELECTION

Fastener selection should always be based on achieving the lowest installed cost while providing the required performance. In terms of lowest cost, a rivet type of fastener would normally be the best selection. There are, however, limitations. These are:

1. Structure Material - if the structure is aluminum or similar strength material, a conventional titanium rivet cannot be used without distortion problems and excessive expansion of the structure adjacent to the driven button. Special titanium rivets have been developed for use in aluminum. These will be discussed in the following section.

2. Fastener Size - the higher strength Beta III rivets can be practically driven with manual impact type rivet guns only up to 3/16 inch diameter. The lower strength CP40 rivets can be practically driven manually up to 1/4 inch diameter and the M172 alloy (55% Columbian) up to 3/8 inch diameter.

With rivet squeezing equipment, the force capabilities designate the limits. The squeeze requirements are:

			<u>Regular Upset (lbs)</u>	<u>Oversqueeze for Fatigue (lbs)</u>
Beta III	-	3/16	- 11,000	18,000
		1/4	- 20,000	32,000
		3/8	- 45,000	72,000
CP40	-	3/16	- 5,500	
		1/4	- 12,000	
		3/8	- 21,000	
M172	-	3/16	- 3,000	
		1/4	- 6,500	
		3/8	- 12,000	

It should be noted here that Boeing has developed an electromagnetic riveting system that utilizes two, precisely synchronized, semi-portable guns to drive a rivet. With this equipment, a rivet is upset in 1/2000 of a second. Initially, this equipment was developed to drive aluminum slug rivets up to 3/8 inch diameter to a precision, repeatable interference profile. It has been demonstrated that this equipment can also be used to reliably upset pre-manufactured head Beta III rivets. Sizing up this equipment to handle larger forces and diameters is relatively easy in comparison to large, stationary squeeze machines. A manufactured head rivet is specified because it is not practical to use slug rivets of titanium. Flush shaving of an installed slug is excessively difficult and impractical.

3. Access - if open access does not exist, the electromagnetic equipment cannot be practically utilized; panel or part size will also limit practical application of portable or stationary squeeze equipment.

4. Clamp-Up - if a high clamp-up is required for a tension application or a high load transfer shear application, a titanium rivet type fastener cannot provide this degree of clamp-up. In fact, a squeezed titanium rivet, with the springback that occurs after upset, will provide very little preload in the joint.

In aircraft construction, non-specialized bolt type applications up to 3/8 inch diameter normally utilize either a Hi-Lok type or lockbolt type of fastener. The lockbolt can be installed quicker by manufacturing personnel and its break-tang pull-up load provides greater assurance of initial component clamp-up. The lockbolt type of fastener does have installation access limitations that the Hi-Lok type fastener does not. Thus, the lockbolt type fastener is usually specified as the preferred steel fastener with Hi-Lok types used in limited access locations. With titanium fasteners, however, the cost of the additional material in the break off tang of a lockbolt makes it more difficult to provide a competitive procurement price. Thus, a singular type of titanium fastener for the application under discussion is usually specified.

SPECIAL FASTENERS OR SYSTEMS

With some exceptions, most special fasteners or systems have been developed to improve the fatigue performance of joints in aluminum structure or to reduce the installed costs for such fatigue rated systems. Even though many of these fasteners were developed specifically in titanium this does not preclude the use of other alloys for the specific fastener concepts. However, in the aircraft industry, the continuing demand for improved performance and the associated weight reductions required will probably result in a continued and increasing use of titanium fasteners. Of the many special concepts that have evolved, only those we consider most significant or of most probable application will be discussed.

Taperlok- this fastener has a tapered shank and is inserted into an interference fit tapered hole. The prestressing caused by the interference improves fatigue performance. Until recently, it has been the primary non-aluminum fastener available for fatigue improvement and is normally considered the baseline for fatigue comparison of other systems. It should be noted that the interference that produces the best fatigue performance with the Taperlok system is not necessarily the best value for apparent interference with other systems. This is especially so when rivet type systems of titanium are used.

Another factor relative to flush head, titanium Taperloks is of importance. When used in aluminum structure the lack of any prestressing from shank interference in the countersink zone can be offset with a steel Taperlok via high torque preload. Examination of fatigue data indicates that a conventional 100° head titanium Taperlok is not capable of equivalent fatigue performance. This is probably the result of lessened pressure in the countersink extremities from the lower modulus of the titanium as evidenced by fatigue failure origins of all titanium Taperlok installations at the countersink/skin juncture. To offset this problem (if necessary), the titanium Taperlok would require a modified head design such as the Boeing 70° head driven into a mismatching 82° countersink or the interference fit 82°/10° Boeing wedge head design.

Boeing PT Bolt - this is a straight shank titanium fastener that was developed as a lower cost alternative to the tapered shank fastener system for use in aluminum structure. Its use is practically limited to 3/8 inch diameter, whereas the tapered shank system is not so limited. The degree of interference used with this fastener to achieve fatigue performance (0.003 to 0.006 inch) dictates that it must be bare (properly lubricated) or have a coating that will not strip on installation. As currently used, this is a phosphate flouride coating. The entry on this fastener is radiused to allow interference installation without hole damage; to assure this, it was found that a rolled finish was necessary on this radius. Another feature is a 70° included angle head with a generous head to shank fillet and a slight crown on top. The 70° head is manually impact driven into a mismatching 82° countersink. This deforms the countersink and provides the necessary prestressing in this zone as well. The crown serves to allow this driving without danger of contacting the surface of the structure. For added galvanic corrosion protection, the countersink is primed with a chromated epoxy primer and allowed to dry before fastener installation. The drying is necessary to retain the primer with the degree of "wiping" involved in fastener installation.

It is interesting to note that the concern shown over the years about the notch sensitivity of titanium and the chamfering provided in holes for the head to shank fillet may not have been necessary. That is, the titanium PT bolt has shown (at least with the 70° head design) to be capable of handling a significant interference in this area.

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Rivbolt - this is currently a Beta III titanium rivet type of fastener. It was originally developed for use in titanium structure, but its initial usage has been in aluminum structure as a lower cost alternative to the tapered shank fastener system. The rivet is installed with a small, square cross section collar adjacent to the structure on the driven button side. A pre-manufactured head with a slight crown is on the other end. During installation, the collar is restrained from excessive expansion by the installation tooling. If precise tooling and precise upset pressures are used, this fastener can be used for fatigue critical applications. The crown on the head serves to produce expansion in the shank adjacent to the head when driven with a flat tool. The tooling on the other end must prevent excessive expansion of the collar on one hand, but it must allow some on the other. If no expansion of the collar is allowed, the shank will treat the collar like an extrusion die and there will be no expansion immediately adjacent to the collar within the hole.

It is interesting to note that this fastener was originally developed with the Ti-6Al-4V alloy. This seemed to result in some variation in expansion results because the ductility of the Ti-6Al-4V varies in its allowed heat treat range. In addition, the Ti-6Al-4V required use of a directional collar that had a radius or chamfer on one side of its bore. This radius was required to prevent cracking of the button on upset and to enhance the flow of metal. A changeover to the Beta III alloy allowed use of a non-directional, square cross section, symmetrical collar,

This fastener can also be used to some advantage in titanium structure to prevent distortion via a more uniform expansion profile.

The apparent interference produced with this titanium fastener in aluminum structure is also of interest. Apparent interference (with regard to probable fatigue performance) is usually defined by calculating the difference between the original hole diameter and the final rivet diameter. With an aluminum rivet, the final result is a rivet with some remaining interference in a partially yielded hole. With the greater comparative springback of the titanium Rivbolt, the end result is a net fit fastener in a yielded hole. Such yielding is similar to that achieved with cold-working to produce a yielded compressive zone around the hole. In the higher yield strength 7000 series aluminum alloys and in titanium structure, this could prove to be especially beneficial.

Unfortunately, the Rivbolt requires relatively high installation forces to produce the required results. This currently limits the fastener diameters or the reach that can be used for this fastener. The electromagnetic riveting system appears to offer potential for eliminating this current restriction.

Wedgehead Lockbolt

This is a fastener developed at Boeing as a second generation alternative to the tapered shank fastener system and as a lower cost, manual installation alternative to the Boeing PT bolt. This is a titanium or steel lockbolt with an 82°/10° double angle head. The fastener is installed into a straight, interference fit hole with an 82°/8° interference fit countersink. The latter provides the necessary interference for fatigue performance in the countersink with a definite depth control not requiring skill to install. The fastener is held in place with an aluminum or titanium self-sealing, swaged on collar. The seal is provided with a small, integral, circular fin on the collar. The advantages for this fastener are use of a low cost collar versus an expensive seal nut, fluid-tightness on both ends of the fastener and easier installation.

Bimetal Rivet

This is a unique, new rivet type fastener of titanium that appears to have excellent potential for application. The fastener, as originally configured, has a Ti-6Al-4V titanium shank with a protruding or 100° flush head and a friction welded end of CP titanium. This provides a high strength shank with an easily driven end to hold the fastener in place. The friction welding process is one that lends itself to practical production of the bimetal joint and one that extrudes all impurities from the joint as it is produced. The resulting joint has no cast structure and has proven excellent in static and fatigue strength tests.

A recent evolution of this concept has been use of the M172 alloy for the welded on end to produce a high strength rivet type fastener that can be upset as easily as an aluminum rivet.

Since the upsetting of the softer end only serves to hold the fastener in place and does not produce any hole filling expansion of the shank, this fastener must be driven into an interference fit hole when the installation requires fatigue improvement. The lack of any threads allows the end of this fastener to be ideally tapered for such

interference installations. Additionally, the lack of any secondary components such as collars or nuts coupled with the lower upset forces makes this fastener ideally suited for installation on existing automatic riveting equipment.

For fatigue critical installations, it is our opinion that a fastener head design such as the wedgehead will have to be incorporated to provide the maximum fatigue performance.

Standard Fasteners with Mandrel/Sleeve Prestressing

Boeing has developed a system of prestressing a fastener hole in aluminum or titanium structure in such a way that fatigue performance can be achieved with standard bolt type titanium fasteners. This process can be used for any diameter although it is especially applicable above 3/8 inch diameter in aluminum structure as an alternative to the tapered shank fastener system not covered by the other alternative systems.

The prestressing is accomplished by pulling a tapered mandrel through a thin wall, split, disposable, pre-lubricated sleeve. The lack of direct contact with the highly reactive aluminum or titanium hole allows a high degree of expansion to be used to produce a large yielded, compressive zone around the hole. The process also allows use of a one-man, one-side operation.

In summary, titanium fasteners offer potential weight savings to the designer at a cost of approximately \$30 per pound of weight saved. Proper and least cost usage must take into consideration type of fastener per application, galvanic couples and installation characteristics of protective coatings, cosmetic appearance, paint adhesion, installation forces and methods available and fatigue performance required. It is hoped that the content of this paper has shed some light on these considerations.